Characterization of Subsurface DNAPL Movement with Ground Penetrating Radar and Inverse Multiphase Flow Simulations

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Abstract

The presence of dense non-aqueous phase liquid (DNAPL) source zones in the subsurface is a limiting factor in the remediation of sites affected by the uncontrolled release of DNAPLs. For successful remediation, the distribution of the DNAPL source zone must be characterized and the DNAPL locations in relation to material permeability contrasts at large and small scales will determine the effectiveness of alternative remedial techniques. The goal of this research is to provide the necessary information to determine the best remedial strategies. Four related investigations evaluate the potential for using ground penetrating radar and inverse multiphase flow simulations to characterize subsurface DNAPL movement and identify the strengths and limitations of the procedure. The following four paragraphs are the abstracts from each of those investigations, which are presented in Chapters 2 through 5 of this dissertation.

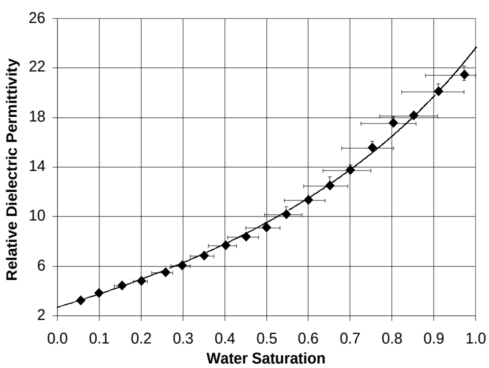

Figure 2.4: Weighted BHS curve.

For accuracy, an iterative Bruggeman-Hanai-Sen (BHS) mixing model with an air/water/sand system must consider which two-material end member (air/sand or water/sand) to use as the matrix. For a given porosity, a new weighted BHS model provides the best match to measured data. Two BHS curves, one with air/sand as the matrix and one with water/sand as the matrix, are weighted based on the water saturation.

Perchloroethylene (PCE) saturations determined from GPR surveys are used as observations for inversion of multiphase flow simulations of a PCE injection experiment, allowing for the estimation of optimal intrinsic permeability values. Synthetic simulations reveal that saturation data alone are sufficient to estimate optimal

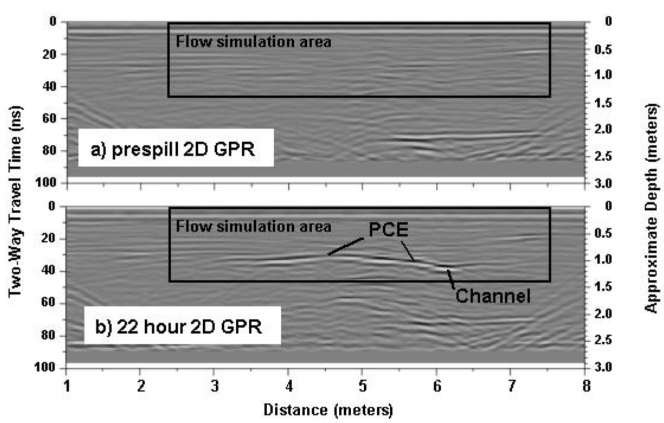

Figure 3.2: 500 MHz GPR data for Borden PCE injection.

intrinsic permeability values, but the character and magnitude of error in the saturation data are critical to accurate estimation. The resulting fit statistics and analysis of residuals (observed minus simulated PCE saturations) are used to improve the conceptual models of permeability zones and capillary pressure-saturation relationships. Remaining bias in the residuals is attributed to the violation of assumptions (lack of flat, infinite, horizontal layers) in the one-dimensional GPR interpretation due to multidimensional influences. However, this bias does not affect the calculation of the optimal permeability values. The effort to improve model fit and reduce residual bias decreases simulation error even for an inversion based on biased observations. This effort is thus warranted and provides information on bias in observation data when this bias is otherwise difficult to assess.

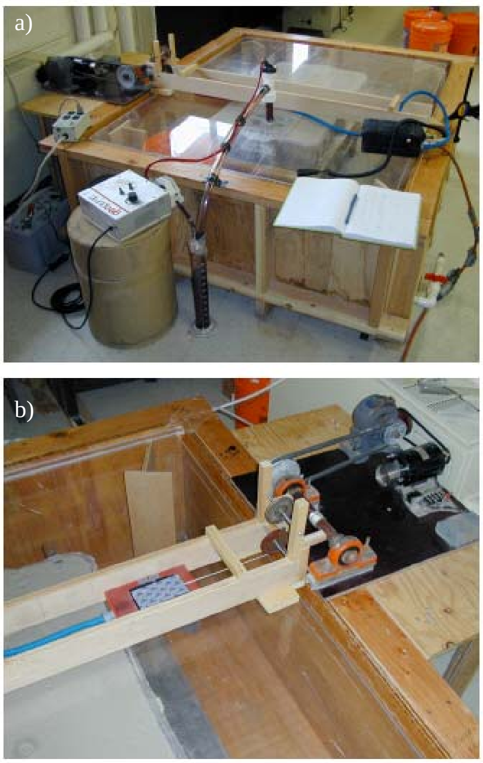

Figure 4.5: Photograph of: a) sand tank, injection system, and GPR antenna track and pulley; and b) close up photograph of GPR antenna, track, and pulley system.

Ground penetrating radar (GPR) is used to track a DNAPL injection in a laboratory sand tank. Before data reduction, GPR data provide a qualitative measure of DNAPL saturation and movement. One-dimensional (1D) GPR modeling provides a quantitative interpretation of DNAPL volume within a given thickness during and after the injection. This is confirmed qualitatively by visual inspection of cores and two-dimensional GPR modeling. DNAPL saturation in sub-layers of that thickness could not be quantified because calibration of the 1D GPR model is non-unique when both permittivity and depth of multiple layers are unknown. Accurate quantitative interpretation of DNAPL volumes using 1D GPR modeling requires: 1) identification of a suitable target that produces a strong reflection and is not subject to any multidimensional interference; 2) knowledge of the exact depth of that target; and 3) use of two-way radar-wave travel times through the medium to the target to determine the permittivity of the intervening material, which eliminates reliance upon reflection amplitude. With geologic conditions that are suitable for GPR surveys (i.e., shallow depths and low electrical conductivities), the procedures in this laboratory study can be adapted to a field site to identify DNAPL source zones after a release has occurred.

A laboratory-scale DNAPL injection is monitored using ground penetrating radar (GPR). Saturation of DNAPLs, determined using the GPR data, provides calibration data for multiphase flow simulations. This paper investigates the value of GPR-derived DNAPL saturations as observations for inversion of multiphase flow simulations for the purpose of characterizing subsurface heterogeneities. The capillary pressure-saturation function and intrinsic permeability of the #45 Ottawa sand used in the experiment is measured, but the permeability varies over an order of magnitude once it is sifted into a tank. Inverse multiphase fluid flow simulations are used to estimate intrinsic permeabilities and the resulting fit statistics and analysis of residuals (observed minus simulated DNAPL saturations and observed minus simulated injection rates) are used to improve the conceptual model of permeability heterogeneities. An inverted simulation with homogeneous sand produces a permeability value that is 15% less than the measured vertical permeability. However, the fit statistics and residuals indicate an incorrect conceptual model of permeability. Additional simulations are explored using different conceptual models of permeability zones. These simulations indicate the importance of fine-scaled permeability variations and lead to an improved fit of simulated versus observed DNAPL mass distribution and injection rates. Inversion of the multiphase flow simulation is non-unique with respect to the geometry and permeability values of those zones. These fine-scaled permeability variations are imaged by the GPR data, but the interpretation of the geometry of the zones is non-unique. Future application of GPR and inverse multiphase flow simulations to determine DNAPL flow must include a procedure to minimize this geometry non-uniqueness in order to completely identify smaller-scale permeability contrasts.

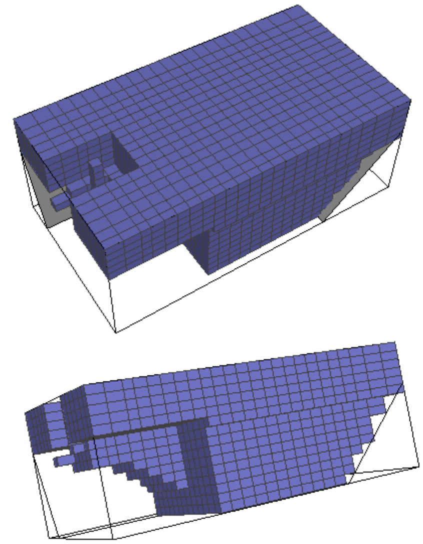

Figure 5.6: Initial multiphase flow simulation grid for tank.

Full document

(http://crustal.usgs.gov/team/Ray_Johnson/Johnson_thesis.pdf, PDF Format, 5.9 MB)

Thesis Publications

Each thesis chapter will be published as individual research papers. The current publications as of October, 2003 are:

Johnson, R.H., and Poeter, E.P., 2003, Interpreting DNAPL saturations in a laboratory-scale injection with GPR data and direct core measurements: U.S. Geological Survey Open-File Report 03-349, 40 p. (http://pubs.usgs.gov/of/2003/ofr-03-349)

Related Publications

Johnson, R.H., and Poeter, E.P., 2002, Key factors for characterizing DNAPLs within heterogeneous aquifers using ground penetrating radar [abs.]: Geological Society of America, Abstracts with Programs – 2002 Annual Meeting. (http://gsa.confex.com/gsa/2002AM/finalprogram/abstract_40655.htm)

Johnson, R.H., and Poeter, E.P., 2001, Inverting multiphase flow simulations with DNAPL saturation observations estimated from geophysical surveys *in* Proceedings of the MODFLOW 2001 and other Modeling Odysseys, eds. Poeter, Zheng, and Hill, International Ground Water Modeling Center, Colorado School of Mines, Golden, CO, 976 p.

Johnson, R.H., Sneddon, K., Olhoeft, G., Poeter, E., McCray, J., and Powers, M., 1999, The simultaneous use of inverse modeling and ground penetrating radar data to enable the successful use of DNAPL flow models for design of remedial action [abs.]: Geological Society of America, Abstracts with Programs – 1999 Annual Meeting. (http://rock.geosociety.org/absindex/annual/1999/51013.htm)

Poeter, E.P., and Johnson, R.H., 2002, Residual bias in a multiphase flow model: calibration and predition, in Calibration and Reliability *in* Groundwater Modeling: A Few Steps Closer to Reality (Proceedings of ModelCARE'2002, Prague, Czech Republic), International Association of Hydrological Sciences Redbook, Publ. No. 277, p. 259-266. (http://www.cig.ensmp.fr/~iahs/redbooks/a277/27736.htm)
Link to slide show presented at the ModelCARE'2002 conference is http://www.mines.edu/~epoeter/research/gprdnapl/slides_ep_ModelCare2002/ModelCare2002_gpr_dnapl.htm

Sneddon, K.W., Powers, M.H., Johnson, R.H., and Poeter, E.P., 2002, Modeling GPR data to interpret porosity and DNAPL saturations for calibration of a 3-D multiphase flow simulation: U.S. Geological Survey Open File Report 02-451, 29 p. (http://pubs.usgs.gov/of/2002/ofr-02-451/)